Climate and climate variability of the wind power resources in the Great Lakes region of the United States

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[1] The climate and climate variability of low-level winds over the Great Lakes region of the United States is examined using 30 year (1979–2008) wind records from the recently released North American Regional Reanalysis (NARR), a three-dimensional, high-spatial and temporal resolution, and dynamically consistent climate data set. The analyses focus on spatial distribution and seasonal and interannual variability of wind speed at 80 m above the ground, the hub height of the modern, 77 m diameter, 1500 kW wind turbines. The daily mean wind speeds exhibit a large seasonal variability, with the highest mean wind speed (~6.58 m s^{-1}) in November through January and the lowest (~4.72 m s^{-1}) in July and August. The spatial variability of the annual mean winds is small across the entire region and is dominated by land-water contrasts with stronger winds over the lake surface than over land. Larger interannual variability is found during the winter months, whereas smaller variations occur in mid to late summer. The interannual variability appears to have some connections to El Niño-Southern Oscillation, with lower mean wind speeds and more frequent occurrences of lulls during major El Niño episodes. Above-normal ice cover of the Great Lakes appears to be associated with slightly lower wind speeds and vice versa. According to NARR data and the criteria established by wind energy industry, the areas over Lake Superior, Michigan, and Ontario appear to be rich in wind resources, but most land areas in the region are either unsuitable or marginal for potential wind energy development.

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1. Introduction

[2] Recently, the increasing interest in wind energy as a viable renewable energy resource has prompted numerous investigations on low-level wind climatology and wind power potentials for different regions around the world. For example, *Czisch and Ernst* [2001] documented a network of wind farms over parts of Europe and Northern Africa. Using wind data from surface and sounding networks, *Archer and Jacobson* [2003] studied spatial and temporal distributions of winds at 80 m aboveground in the United States, and they later extended their study to quantify the potential wind energy resources over the entire globe [*Archer and Jacobson*, 2005]. *Elliott et al.* [1986, 2001a, 2001b, 2001c, 2002, 2003] produced wind energy resource atlases for the United States and several other countries around the world. Recently, *Kircsi* [2008] assessed wind energy potential for Hungary using 50 year records from a global reanalysis data set [*Kalnay et al.*, 1996]. *McVicar et al.* [2008] developed an Australia-wide 0.01° resolution daily wind speed data set for 1975–2006 using data from an expanded anemometer network.

[3] The current study focuses on wind energy potential in the Great Lakes region of the United States. The eight-state Great Lakes region is suffering the worst economic downturn since the Great Depression. Development of renewable energy, such as bio-energy and wind energy, may offer a much-needed economic boost in this region. The presence of the Great Lakes provides vast tracts of open area unimpeded by topography and vegetation and the de-urbanization that has been going on in some cities such as Detroit, Michigan creates large open and unobstructed areas that could be excellent for the development of wind energy. As wind energy development expands from the wind resource-rich Northern Great Plains [*Archer and Jacobson*, 2003] into the Great Lakes region, understanding the regional distribution of wind resources and the climate variability is becoming increasingly important.

[4] Although several studies have investigated wind climatology and climate variability at locations over the Northern Great Plains using long-term climate data [e.g., *Klink*, 1999, 2002, 2007; *Harper*, 2005; and *Harper et al.*, 2007], no

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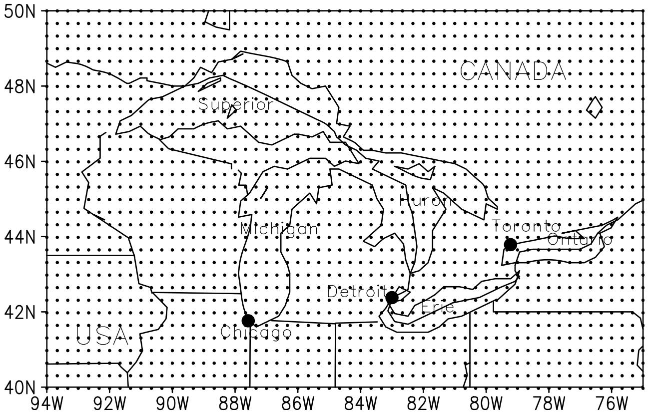

Figure 1. The domain of the study (40°N~50°N, 94°W~75°W) and the grid points in the NARR data set.

studies have, to our knowledge, focused on the spatial and temporal variability of wind resources over the Great Lake region. The region, however, has been included in several studies of wind resources of the entire United States. *Archer and Jacobson* [2003] has shown that the majority of the Great Lakes region falls in between wind power class 2 (marginal for wind farm) and class 3 (suitable for wind farm development with near future technology). This between marginal and suitable classification calls for further investigation, especially considering some limitations of this particular study. One limitation was that the study was based primarily on the extrapolation of surface wind observations that are subject to substantial local influences to heights typical of modern wind turbines [*McVicar et al.*, 2007, 2010]. Another major limitation of their study was that data from only 1 year (year 2000) were employed without consideration of interannual variability [*Archer and Jacobson*, 2003], which is likely to result in a bias of wind power potential.

[5] Recognizing the critical importance of understanding climate variability for developing robust assessments of wind resources, *Pryor et al.* [2009] examined near surface wind trends from 1975 to 2005 over the contiguous United States. Their study compared climate trends determined from eight data sets including (1) two observational data sets, (2) four reanalysis data sets, and (3) two data sets from regional climate model (RCM) simulations of the current climate. Their results revealed substantial differences in temporal trends among the data sets, with the two observational data sets and one RCM data set exhibiting declining trends across the United States, whereas all four reanalysis data sets and one RCM data set displayed converse trends. The study found no clear consensus of the eight data sets with respect to whether or not there is a link between the changes in annual mean wind and the interannual variability. Over the Great Lakes region, the comparisons show that the reanalysis data sets exhibit considerable skill in reproducing the observed annual mean wind speed over the region but fail to describe the observed negative trends. The study points to increased roughness lengths resulting from urbanization and reforestation as potential causes for the observed downward trend, although the dominant source of temporal trends remains uncertain. It is also unclear what may have caused the discrepancies in the temporal trends between the observed and the reanalysis data sets and RCM output. Midlatitude terrestrial observational declines of near-surface (i.e, 10 m or less) wind speeds have been documented in both hemispheres [*McVicar et al.*, 2008], and comparisons of the observed trends with those from the three major reanalysis data sets over Australia from 1979 to 2001 showed that while the reanalysis data sets produced declining wind speed (in agreement with observation), the magnitude of this trend was only 1/3 to 1/6 of that observed [*McVicar et al.*, 2008].

[6] This paper presents an investigation of the spatial distribution of the modern wind turbine level (80 m above ground level or AGL) wind speed climatology across the Great Lake region. In addition to mean annual wind speed, the study also examines climate variability including seasonal and interannual variability. The study tests the hypothesis that, similar to temperature and moisture, the characteristics of the low-level winds are modified by the thermodynamic and dynamic effects of large water bodies in the region. The study also investigates the possible connection between the interannual variability of low-level winds across the Great Lakes region and the changes in large-scale circulation patterns associated with El Niño-Southern Oscillation (ENSO).

[7] The data set employed for the study is described in section 2, which also discusses the advantages and disadvantages of the data set and its validation. Section 3 presents the climate and climate variability of wind speeds over the region. This is followed by discussions of wind power potentials across the region in section 4. A summary of the results and conclusions are presented in section 5, together with a discussion of the limitations of the current study and future work.

2. Data Source

2.1. Data Description

[8] The data set used for the current study is the North American Regional Reanalysis or NARR [*Mesinger et al.*, 2006]. The NARR data set, produced by the National Center for Environmental Prediction (NCEP), is a long-term, dynamically consistent, and high spatial (32 km) and temporal (3 hourly) resolution atmospheric and land surface

Table 1. Site Information of Upper Air Rawinsonde Sounding Stations Used in the Comparison

Abbreviation	Station	Longitude (°W)	Latitude (°N)	Elevation (m)	Periods
GRB	Green Bay, WI	88.13	44.48	214	1979~2008
BUF	Buffalo, NY	78.73	42.93	215	1979~2008
DTX	Detroit, MI	83.46	42.70	329	1995~2008
APX	Gaylord, MI	84.71	44.91	446	1997~2008
INL	International Falls, MN	93.37	48.56	361	1979~2008

Table 2. Evaluation Statistics of Mean Daily Wind Speed[a]

	Sounding		NARR					
	Mean	s.d.	Mean	s.d.	Corr.	Bias	RMSE	SDE
GRB	5.62	0.67	5.80	0.84	0.73	0.18	0.60	0.33
BUF	6.18	0.85	5.54	0.89	0.81	−0.64	0.84	0.30
APX	5.36	0.99	5.95	0.97	0.84	0.59	0.81	0.31
DTX	5.92	1.12	5.70	1.07	0.90	−0.22	0.55	0.25
INL	5.35	0.52	5.82	0.52	0.61	0.47	0.66	0.21
Mean	5.69	0.83	5.76	0.86	0.78	0.08	0.69	0.28

[a]The units are in m s^{-1} except for "Corr." Corr., correlation coefficient; RMSE, root-mean-square error; s.d., standard deviation; SDE, standard deviation of error.

climatology and hydrology data set for the North American domain. The data set was produced using the NCEP mesoscale operational forecast model, the Eta model [*Black*, 1988] (2003 frozen version), and the Eta Data Assimilation System. A horizontal grid spacing of 32 km and 45 vertical layers are used in the production runs that produce a suite of meteorology and hydrology variables 8 times per day from 1979 to present. The input data include all observations used in the NCEP-NCAR (National Center for Atmospheric Research) Global Reanalysis project (hereafter referred to as GR) [*Kalnay et al.*, 1996], additional precipitation data, TIROS Operational Vertical Sounder-1B radiances, radar wind profiler data, and land surface and moisture data. Besides having much higher spatial and temporal resolution and the use of numerous additional or improved observational data sets, the new NARR data set is produced with a more sophisticated land surface model [*Luo et al.*, 2007] and with improved data assimilation algorithms compared to GR, its global counterpart. Thus, it should offer an improved physical depiction of meteorological, climatological, and hydrological variables over GR in addition to the significantly enhanced spatial and temporal resolution for the continental USA [*Mesinger et al.*, 2006].

[9] Of particular interest to this study is the assimilation of observed surface wind into the NARR production runs that has resulted in a significant improvement of NARR 10 m

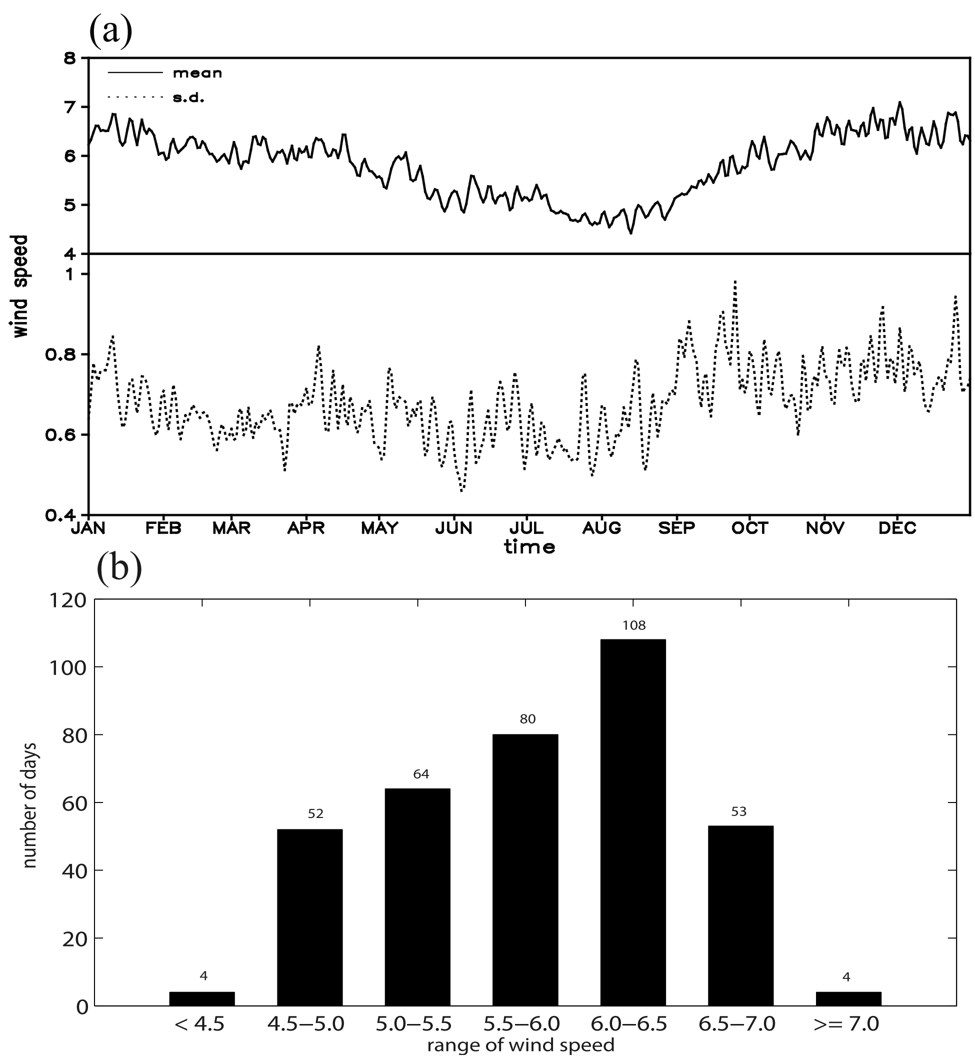

Figure 2. (a) Time series of domain-averaged mean daily wind speed and spatial standard deviation (unit: m s^{-1}) and (b) the number of days in a year when the domain-averaged daily mean wind speeds fall in certain range.

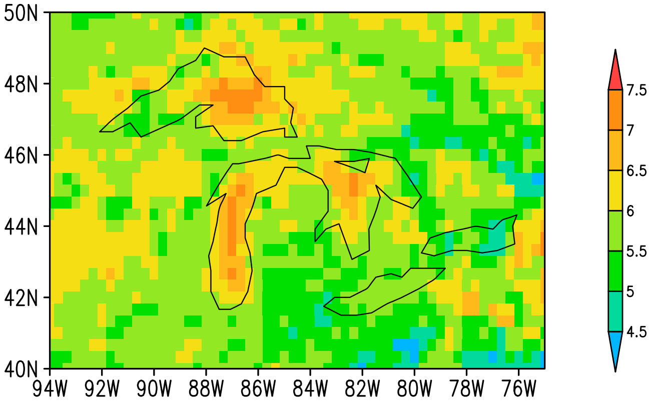

Figure 3. Annual mean wind speed (unit: m s^{-1}) averaged from 1979 to 2008 over the Great Lakes region.

winds compared to its global counterpart. Another very important improvement of NARR data related to the Great Lakes region is the assimilation of high-resolution Great Lakes ice and temperature data that has helped improve NARR's representation of climate over the Great Lakes region [*Mesinger et al.*, 2006].

[10] The NARR data are archived 8 times a day for 29 pressure levels from 1000 to 100 hPa. Below 700 hPa, the vertical interval is 25 hPa, and above 700 hPa, the vertical resolution reduces to 50 hPa. The data span 1 January 1979 to the present and here, we used 30 year data from 1 January 1979 to 31 December 2008. The domain for this study is shown in Figure 1. The daily mean wind speeds over the domain are calculated by first computing wind speed from the archived zonal and meridional wind components starting at 0000 local standard time each day. Wind speeds at 80 m above ground level (AGL) were computed by simple linear interpolation in the vertical. Specifically, the interpolation was done between NARR archived 10 m u and v components and the u and v values at the geopotential height level immediately above 80 m. The geopotential height fields are first subtracted from terrain fields to obtain height above ground (AGL). The vertical resolution of NARR archive is 25 hPa in the lower troposphere. For the study region that is relatively flat with mean elevation 150–350 m above the mean sea level, the nearest level above 80 m is usually the 975 or 950 hPa geopotential height level (Figure 1).

2.2. Data Evaluation

[11] Several studies have validated NARR data against surface and upper air observations. *Mesinger et al.* [2004] showed that NARR surface precipitation fields are in excellent agreement with the observed precipitation. Using rawinsonde sounding profiles from more than 100 sites across United States for a 24 year period (1979–2002), *Mesinger et al.* [2006] showed that temperature and wind profiles in NARR agree well with the rawinsonde sounding profiles and that NARR fits to rawinsondes are considerably better than GR with smaller RMS error from surface to 200 hPa especially in lower troposphere and near tropopause. NARR data also show significant improvements over GR in the 10 m winds and 2 m temperatures with improved diurnal cycle behavior. For the current study, the variable of interest is near-surface wind speed. One of the advantages of NARR over the previous reanalysis data is that 10 m observed winds were assimilated into NARR. A comparison of NARR 10 m wind with observed wind at over 400 surface stations across United States revealed only a slight negative bias (no bigger than −0.5 m s^{-1}) in both summer and winter, which is a huge improvement over GR that shows a considerable positive bias of 1–2 m s^{-1} in winter. In summer, the NARR RMS is smaller, despite no obvious advantage in bias [*Mesinger et al.*, 2006].

[12] To evaluate how accurate the NARR-derived 80 m winds represent the observed wind speeds at the same level, we have obtained rawinsonde soundings from a number of stations in the region for time periods ranging from 14 to

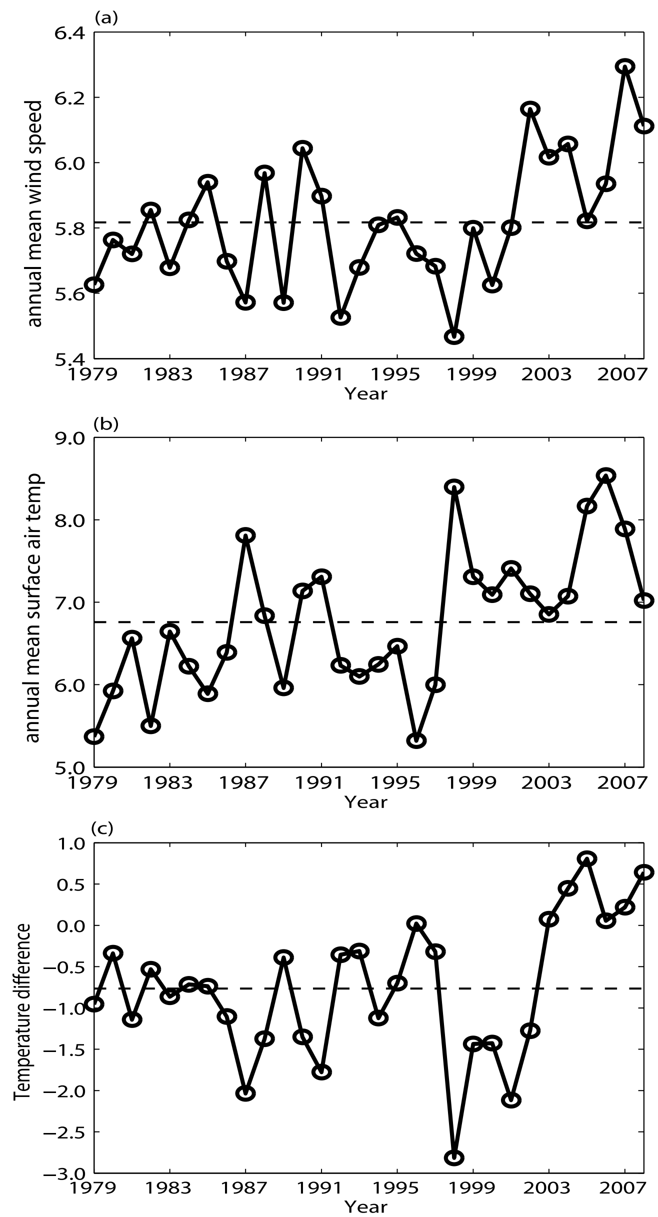

Figure 4. (a) Domain-averaged annual mean 80 m wind speed (m s^{-1}), (b) surface air temperature (°C), and (c) land-water temperature difference for the 30 year period of 1979–2008. Dashed line is 30 year mean.

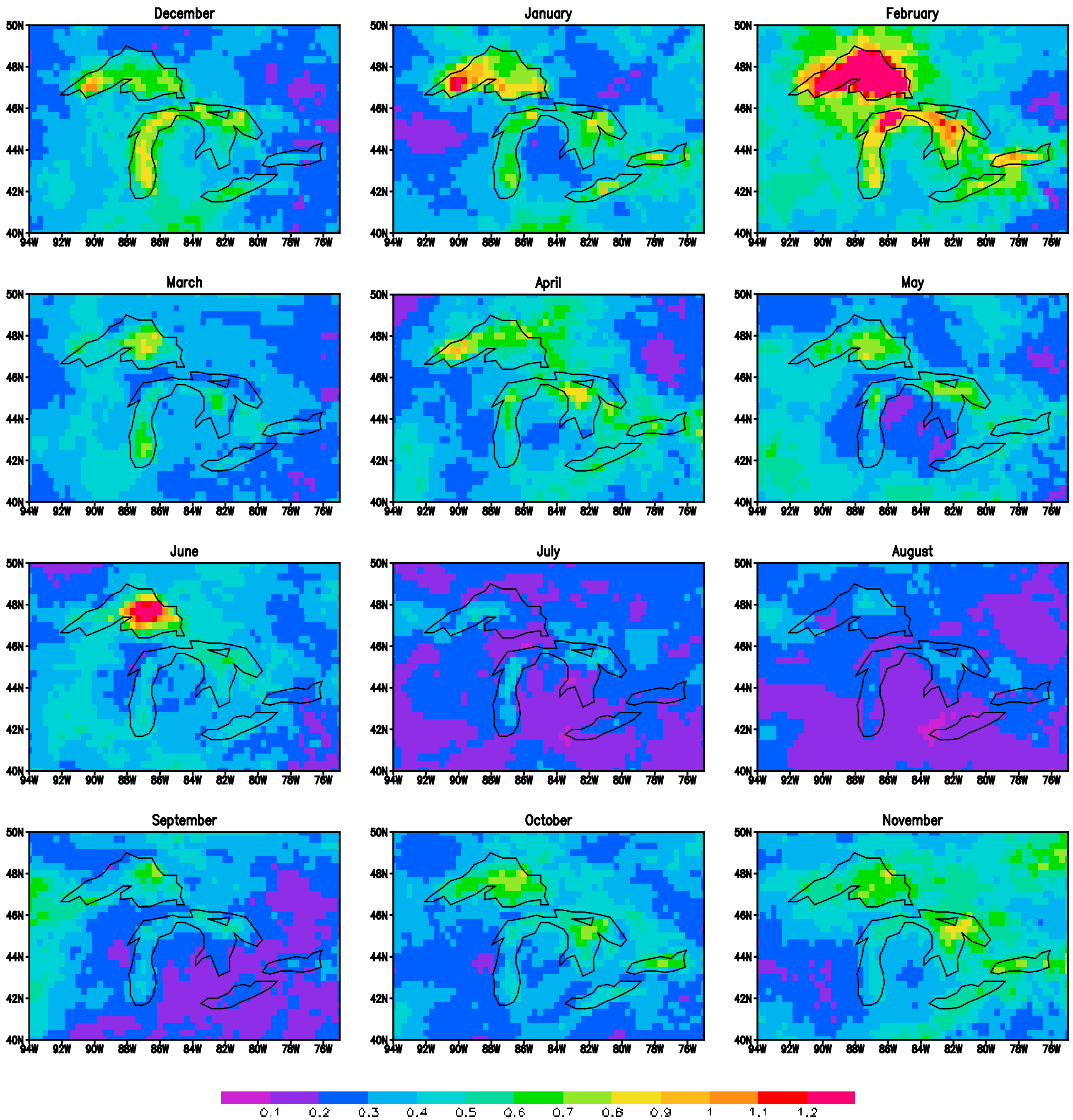

Figure 5. Interannual variability of 80 m wind speed variance (unit: $m^2\ s^{-2}$) for each month of the year.

30 years. The station information is given in Table 1, and the comparison statistics, including correlation, bias, root-mean-square error, and standard deviation of error, are given in Table 2. At all five stations, there is a slight bias in NARR-derived 80 m wind speed, but the sign of the bias differ from one station to another. At Buffalo, NY, and Detroit, MI, the bias is negative, whereas positive bias is found at the other three stations. The bias values range from -0.64 m s^{-1} at Buffalo, NY, to 0.59 m s^{-1}at Gaylor, MI, with the mean bias across all five stations near zero (i.e., 0.08 m s^{-1}). The root-mean-square error range from 0.55 to 0.84 m s^{-1}. The correlation coefficients range from 0.61 at Internal Falls, MN, to 0.9 at Detroit, MI, indicating that the temporal variation of the NARR wind correlate reasonably well with the observed wind variation.

3. Climate and Climate Variability of Wind Speed

3.1. Annual Mean Wind and Spatial Variability

[13] Daily mean 80 m level wind speeds averaged over the entire study area and over the 30 year period are shown in Figure 2a. Also shown in Figure 2a is the standard deviation from the domain-averaged daily mean value, which indicates the spatial variation for a given day across the region. The

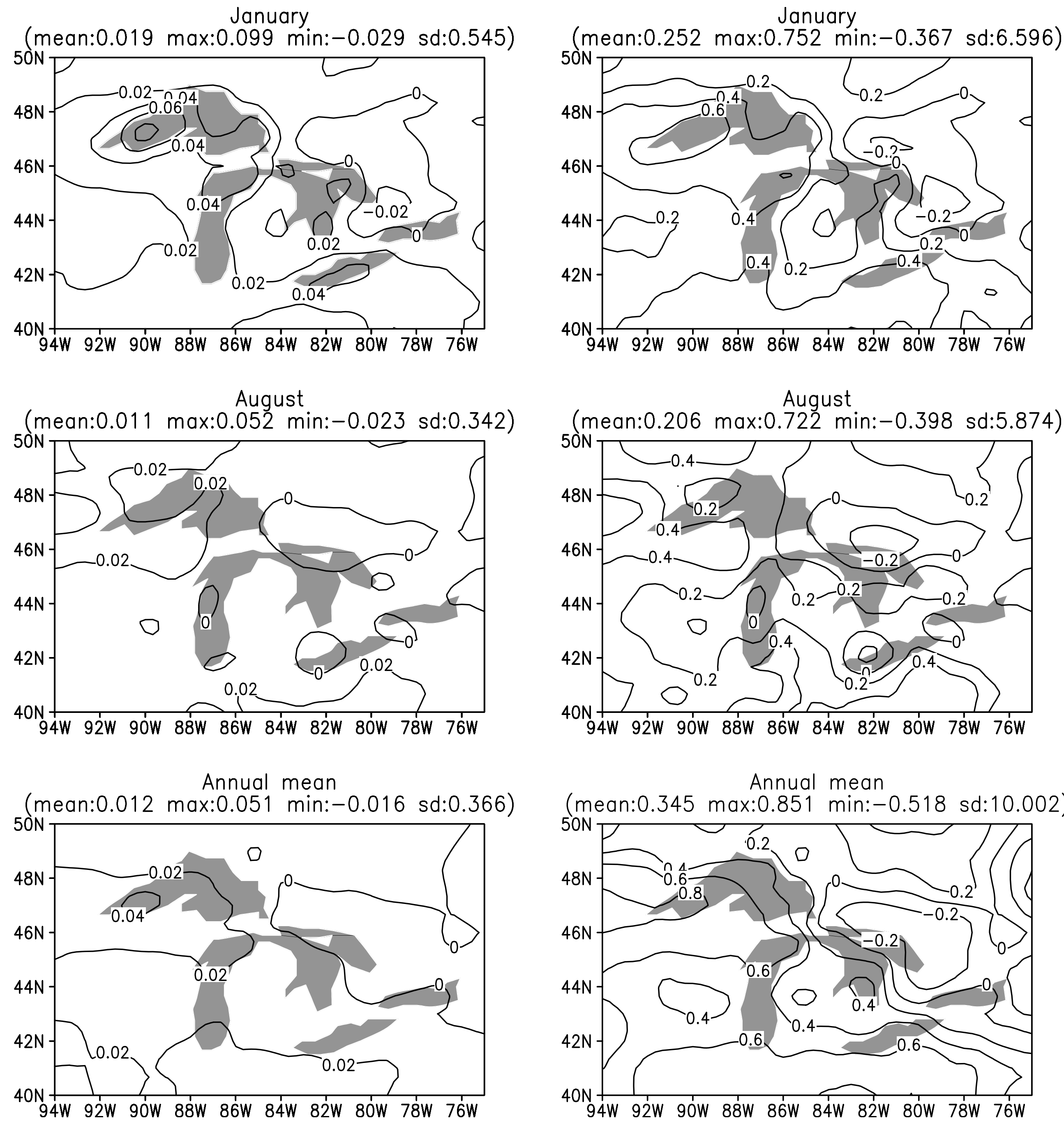

Figure 6. (left)The linear trends (unit: m s^{-1} a^{-1}) and (right) the correlation coefficients for January, August, and annual mean wind speeds for the 30 year period of 1979–2008. The numbers on top of each plot are mean, maximum, minimum, and spatial standard deviation.

daily mean wind speed follows a distinct seasonal cycle. Like much of the country, the mean wind speeds in the Great Lakes region are the strongest in winter and spring when the equator-to-pole temperature and pressure gradients peak, and weakest in summer, a time of diminished latitudinal temperature and pressure contrasts. The strongest winds occur in November through January, whereas the weakest mean winds are found in July and August. The largest spatial variability, as indicated by the highest standard deviation from the domain mean, occurs during the fall season when the transition of synoptic weather regimes occurs. The relatively small standard deviation values suggest that the daily mean wind speed does not vary considerably across the region. The histogram in Figure 2b shows that the domain-averaged daily mean 80 m level wind speed falls in the range of 4–7.5 m s^{-1}. On about half of the days in a year, the daily wind speeds are between 5.5 and 6.5 m s^{-1}, and as expected from a normal distribution, there are only a

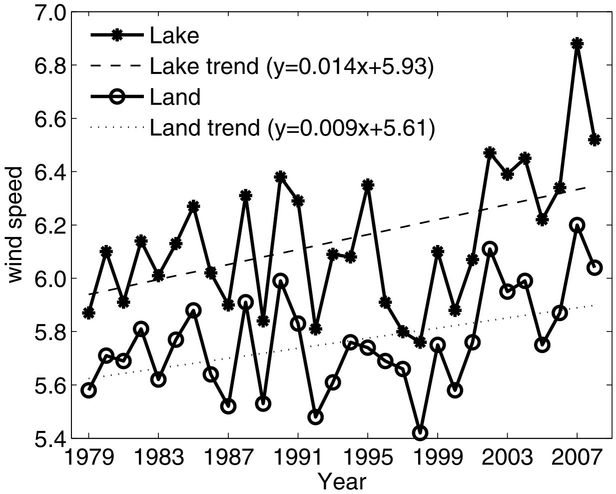

Figure 7. Annual mean wind speed averaged over all land points and all lake points for the 30 year period of 1979–2008.

few days each year when the daily mean wind speeds fall either in the low range between 4 and 4.5 m s^{-1} or in the high range of 7–7.5 m s^{-1}.

[14] The relatively homogeneous spatial wind field over the region, as suggested by the small values of the standard deviation, can also be seen in Figure 3, which shows the 30 year averaged spatial distribution pattern of annual mean wind speed. The values of the annual mean wind speed vary only between 5.5 and 7 m s^{-1} across the entire region. The small spatial variations across the region could imply that the wind variability may be controlled or modulated by regional or large-scale weather systems. It could also be due to the relatively coarse spatial resolution (32 km) of the NARR data that unlikely to capture small-scale variations associated with local factors such as topography [*McVicar et al.*, 2007, 2010] and land use [*Ozdogan and Salvucci*, 2004; *Ozdogan et al.*, 2006].

[15] The spatial variability in the wind field is dominated by land-water contrasts with, as expected, higher winds over the lake surfaces as a result of reduced surface friction. The mean winds appear to be somewhat higher in the western and northern parts than the eastern and southern parts of the region.

3.2. Interannual Variability

[16] The interannual variability of the 80 m level winds over the Great Lakes region is revealed in Figure 4a, which shows the time series of the domain-averaged annual mean 80 m level wind speed for the 30 year period. The time series can be characterized by three periods, each lasting about a decade, during which the wind speed variations exhibited distinct patterns. The first period was from 1979 through 1991 when the mean wind speed over the region oscillated around the 30 year mean value of 5.81 m s^{-1}. The amplitudes of the oscillation were small (less than 0.5 m s^{-1}). The second period, from 1992 through 2001, was characterized by lower than normal wind speeds. This period contained the two years when the domain-averaged annual mean wind speeds were the lowest among the 30 years (5.53 m s^{-1} in 1992 and 5.47 m s^{-1} in 1998). In the last 7 years since 2002, the annual mean winds across the region were all above the 30 year average. The last period contained the 2 years when the mean wind speeds were the highest over the 30 year analysis period (6.16 m s^{-1} in 2002 and 6.29 m s^{-1} in 2007).

[17] The wind speed variations appear to have some connections to the variations of domain-averaged annual mean surface air temperature (Figure 4b). Air temperature has been above normal in the past 10 years after a period of lower than normal air temperature from 1992 through 1997 and a period before 1992 when air temperature experienced more oscillation. The correlation coefficient between surface air temperature and wind speed, however, is small (0.239). The wind speed variation appears to be better correlated with the local land-water temperature contrast as shown in Figure 4c. The temperature differences are determined using grid points close to the shoreline of Lake Michigan. The correlation coefficient between annual mean wind and temperature difference is 0.383. The relatively low correlation is not surprising considering that wind speed at 80 m can be affected by many other factors including topography and vegetation, regional- and large-scale pressure gradients, surface friction, downward momentum transfer by turbulent mixing, and surface moisture conditions [e.g., *McVicar et al.*, 2007; *Ozdogan and Salvucci*, 2004; *Ozdogan et al.*, 2006; among others], and not all of them are well captured by NARR.

[18] Monthly spatial distributions of the interannual variability, as measured by wind speed variances computed using monthly mean values for the 30 year period, are shown in Figure 5. Larger interannual variations of monthly mean wind speed, as indicated by higher variance values, are found during winter (December-January-February, DJF), whereas smaller variations are found in mid and late summer (July and August) and early fall (September). The lower year-to-year variations in summer are due mainly to weaker overall wind speeds in the summer when the region is frequently influenced by high pressure systems [*Eichenlaub*, 1979]. The larger interannual variability of mean winds in

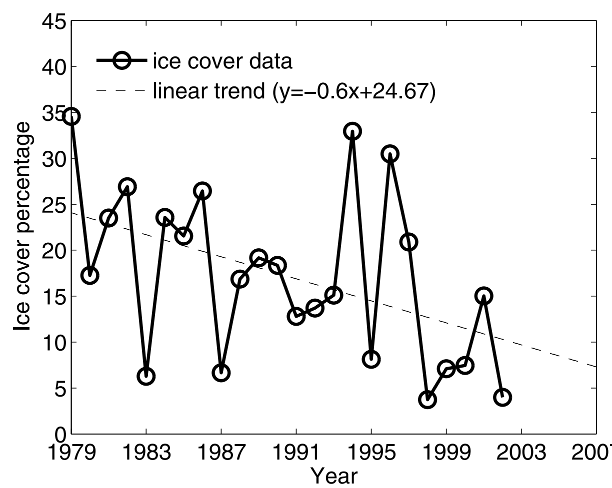

Figure 8. Cold season (December–May) mean ice cover percentage (%) with linear trend based on data downloaded from NOAA's Great Lakes Environmental Research Laboratory Web site.

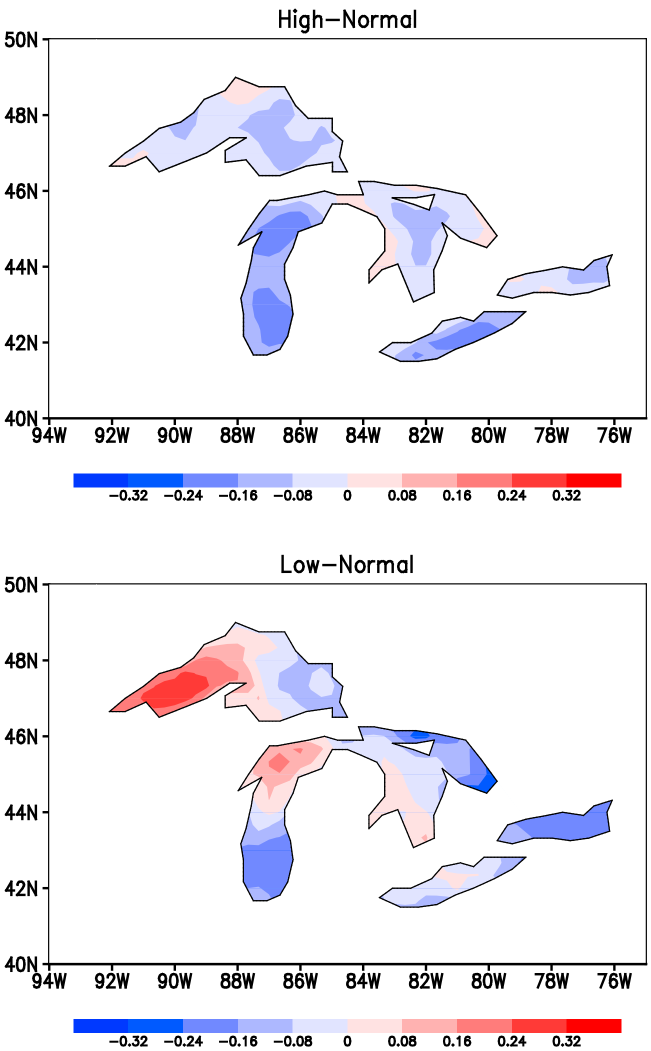

Figure 9. Differences in mean wind speeds (top) between higher than normal and normal ice cover years and (bottom) between lower than-normal and normal ice cover years.

winter or the winter season is partially due to stronger wind speeds and to the winds being more sensitive to the changes in synoptic-scale weather systems, which in turn, are strongly influenced by changes in the polar jet-stream positions [*Eichenlaub*, 1979]. The variations are quite similar between the spring season and the fall season. Areas over the Great Lakes appear to have larger year-to-year wind speed variations over the 30 year period.

3.3. Linear Trends

[19] To further understand the changes in wind speed over the past 30 years and how these changes are distributed spatially over the region, linear regression analysis was performed for the 30 year averaged monthly mean wind at each grid point over the domain. Figure 6 shows the slope of the linear trend, indicating the rate of increase or decrease, as well as the correlation coefficient (domain mean $R = 0.35$ at the 95% confidence level) between the annual mean wind speed and time, which is the year here. The results are shown only for the (1) windiest month (January), (2) calmest month (August), and (3) annual mean. In January, the rate is positive everywhere except for the area east of Lake Huron in Ontario, Canada. The rate of increase is small, however, ranging from 0.02 to 0.08 m s^{-1} per year. The rate of decrease in wind speeds east of Lake Huron is even smaller (magnitude less than 0.02 m s^{-1}). The largest rate of increase, colocated with the highest correlation coefficient, appeared over the Lake Superior region, which indicates that the January wind speeds over this area have been on an increasing trend over the past 30 years. The August results also revealed a generally positive trend in the northwestern and southern parts of the domain and a slightly negative trend on the Canadian side of the Great Lakes region. However, both the rates and the correlation coefficients were quite small in August. The annual patterns revealed a general increasing trend of 0.02–0.04 m s^{-1} per year over the western and southern parts of the region and a small decreasing trend with magnitude less than 0.02 m s^{-1} per year east of Lake Huron and north of Lake Ontario.

[20] The positive trends of 80 m level winds over large areas of the Great Lakes region are different from the findings from several recent studies that indicate a generally declining trend of surface wind speed in the United States including areas of the Great Lakes region [*Pryor et al.*, 2009], over many regions of Australia [*McVicar et al.*, 2008] and in southern Canadian Prairies [*Wan et al.*, 2010]. This decreasing trend of midlatitude terrestrial winds are thought to be likely caused by changes in regional and/or global circulation patterns such as El Niño-Southern Oscillation [*St. George and Wolfe*, 2009] and the expanding of Hadley

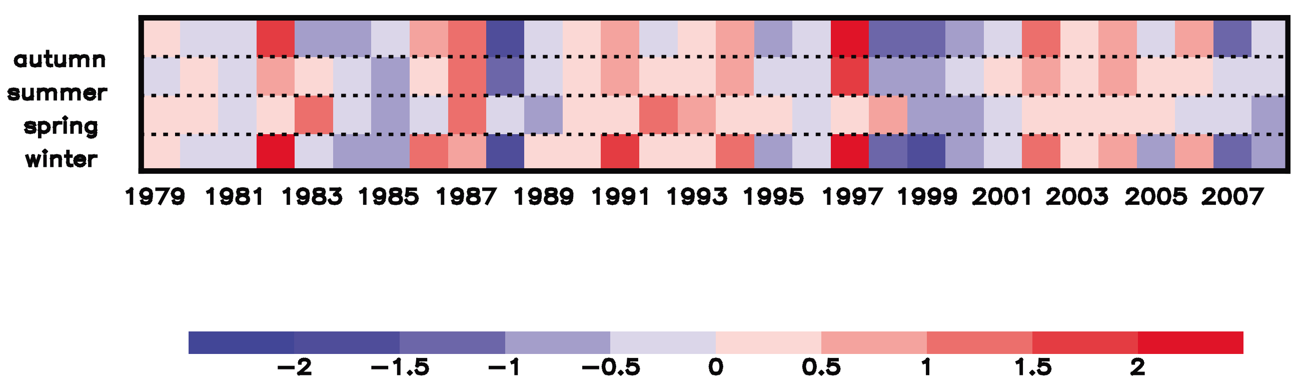

Figure 10. Seasonal mean sea surface temperature anomaly (SSTA) in the Niño 3.4 region (°C) for the 30 year period of 1979–2008.

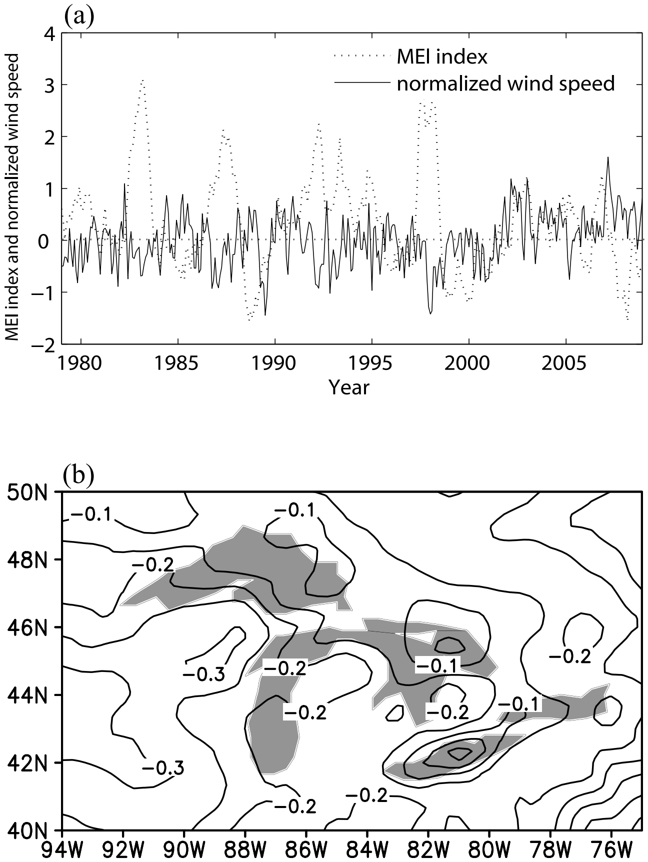

Figure 11. (a) Time series of MEI index for ENSO and domain-averaged normalized monthly wind speed from 1979 to 2008 and (b) spatial distribution of the correlation coefficients between monthly wind speed and monthly MEI index from 1979 to 2008.

cell under global warming [*Lu et al.*, 2009; *Lu et al.*, 2007; *Seidel et al.*, 2008]. *Pryor et al.* [2009] find that the decreasing trends are not captured by any of the reanalysis data sets including NARR. Although the trends of 80 m level winds do not necessarily need to follow those of near-surface winds, which are substantially subject more to local influence, the apparent discrepancy in the linear trends calls for further investigation and caution when interpolating the results of the trends derived from NARR and other reanalysis data [e.g., *Pryor et al.*, 2009; *McVicar et al.*, 2008].

3.4. Impact of Water and Ice Cover

[21] The influence of water surface on wind speeds and their interannual variability are revealed in Figure 7 that shows time series of mean wind speed averaged separately over all land points and all lake points. As expected, the mean winds over the lake surfaces are consistently stronger than winds over the land areas in all 30 years. The two time series vary consistently from year to year and exhibit the same upward trend for the 30 year period, suggesting that changes in regional- and large-scale circulations, instead of local conditions, are likely to be the primarily cause for the interannual variability of wind speed over the region. The amplitudes of variations are comparable between the two time series in some years, and in other years, the amplitudes is larger over water than over land.

[22] Observations of percentages of ice cover over the Great Lakes have shown that the average ice cover exhibit a large interannual variability and has been decreasing in recent decades especially in the last decade (Figure 8). The decreasing trends in the ice coverage are consistent with the increasing trends of cold season evaporation from the Great Lakes [*Li et al.*, 2010].

[23] The connection between ice coverage and wind speed over the lake surfaces are examined by averaging winds separately for years with larger than normal ice cover and those with smaller than normal ice coverage. Figure 9 shows the mean wind speed difference between the above-normal and normal ice cover years and between the below-normal and normal ice cover years. It appears that the increase in ice coverage corresponds to a decrease in wind speed and vice versa. This negative correlation is likely to be related to differences in large-scale circulation patterns between the above and below normal ice cover years. Extensive ice cover is usually associated with southward placement of polar jet streams and more frequent control of cold polar highs and weaker winds over the Great Lake region [*Assel and Rodionov*, 1998; *Rodionov and Assel*, 2000].

3.5. Effect of ENSO

[24] The El Niño-Southern Oscillation (ENSO) is a coupled atmospheric-ocean cycle with a 2–7 year period occurring over the tropical Pacific Ocean. Previous studies have shown that ENSO is an important source of climate variability on interannual time scales for most of the United States including the Great Lakes region [*Nash*, 2002; *Enloe et al.*, 2004]. El Niño episodes typically are associated with a strong jet stream and a greater frequency of storm tracks across the southern part of the United States and less storminess and milder-than-average conditions across the north. La Niña episodes feature a very wave-like jet stream flow over the United States and Canada, with colder and stormier than average conditions across the north, and warmer and less stormy conditions across the south. Although most studies on the connection of ENSO to the climate variability of the United States have focused on temperature and precipitation, few have specifically examined the impact of ENSO on near-surface wind fields.

[25] Several indices have been proposed to classify ENSO. This study uses two indices. The first is the multivariate ENSO index or MEI, a composite index defined by the National Oceanic and Atmospheric Administration (NOAA) that is calculated based on six observed variables (sea level pressure, sea surface temperature, surface air temperature, cloudiness, and surface zonal and meridional wind components) over the tropical Pacific [*Wolter and Timlin*, 1993]. MEI can be considered as a weighted averaged of the main ENSO features contained in the six variables. Positive MEI values represent the warm ENSO phase (El Niño), whereas negative values represent the cold ENSO phase (La Niña). The second ENSO indicator is the seasonal mean sea surface temperature anomaly (SSTA) of the Niño 3.4 region (5°N–5°S, 120°W–170°W) provided by the NOAA's Climate Prediction Center. The cold and warm episodes are based on a threshold of ±0.5°C in the Niño 3.4 region for the 1971–2000 base period. Figure 10 shows the seasonal mean SSTA

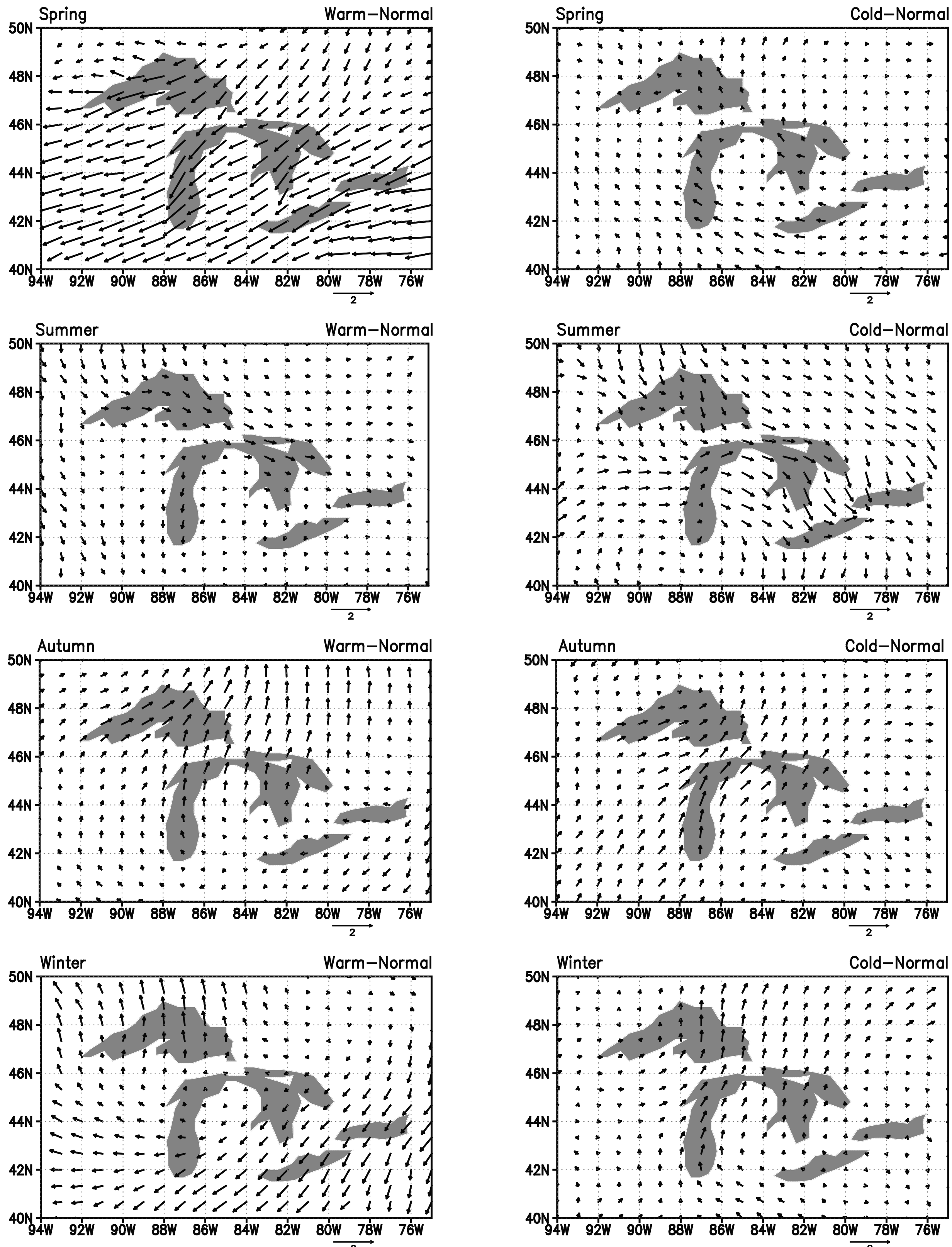

Figure 12. The seasonal mean vector wind differences (unit: m s^{-1}) between the composites of (left) warm event years and normal years and (right) of cold event years and normal years.

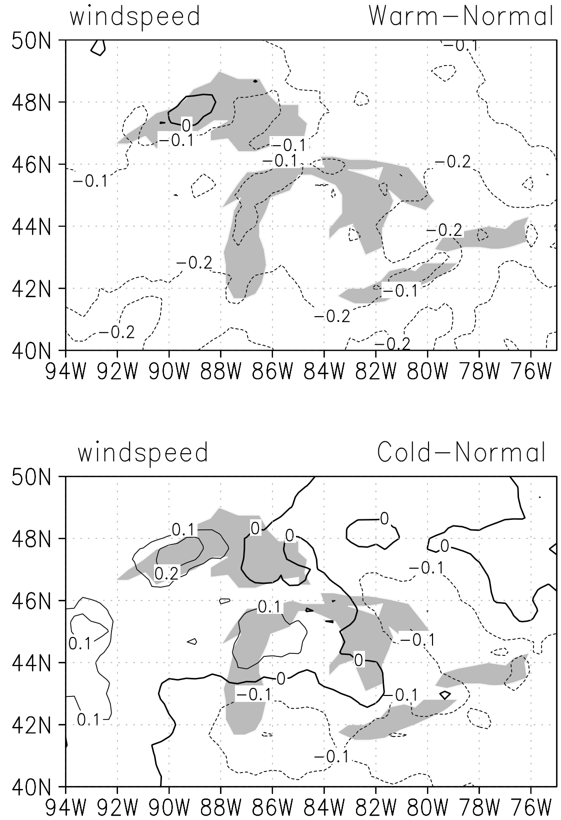

Figure 13. Same as Figure 12, but for annual mean wind speed difference.

values in the Niño 3.4 region and the years for warm, cold, and normal episodes for the analysis period from 1979 to 2008. If MEI instead of SSTA in Nino 3.4 region was used to classify the episodes, the outcome would have been similar.

[26] Figure 11a shows the time series of the domain-averaged annual mean wind speed and the MEI values for the 30 year study period. The negative correlation between the two (with a correlation coefficient of −0.265 at 95% confidence level) suggests that the major El Niño episodes were characterized by reduced wind speeds and more frequent occurrences of lull that would reduce wind power production. The spatial distribution of correlation coefficients across the region is shown in Figure 11b. The negative correlation is consistent across the whole region. Strong negative correlations with coefficients more negative than −0.35 exist in the western part of the region, whereas the lowest correlation occurs in the southeast corner, over Lake Erie and the northeast part of Lake Huron and Lake Superior due possibly to the influence of local or lake effect weather over these areas.

[27] To further quantify the impact of ENSO on low-level wind fields in the region, the mean seasonal 80 m level wind velocities for each of the four seasons were calculated separately for normal, warm, and cold periods based on the classifications in Figure 10. Figure 12 shows the wind velocity differences between the warm periods and normal periods and between the cold and normal periods for each season. The warm episodes, or El Niño events, appear to have stronger influences on spring and winter season mean winds than on summer and autumn season mean winds. In spring, the influence is relatively uniform across the domain, with stronger northeasterly flows over the entire Great Lakes region. The effects are felt differently in different parts of the domain in winter, when stronger southerly winds tend to occur over the northwestern part of the region and stronger easterly and northeasterly winds tend to occur over the western and southeastern parts of the region, respectively. The pattern for autumn is similar to winter, but in summer, the differences are small. The cold episodes, or La Niña events, appear to have somewhat larger influences on summer season mean winds and smaller influences on spring winds. The La Niña effect is also characterized by somewhat larger spatial variability across the region.

[28] Figure 13 shows the differences in annual mean wind speed between warm or cold episodes and normal periods. The differences were negative everywhere across the region for warm episodes, indicating on average a reduction of annual mean wind speed during El Niño episodes. For cold episodes, the differences were positive (an increase in annual mean wind speed) over the western part of the region and negative (a reduction in annual mean wind speed) in the southern and southeastern parts of the region. The differences were slightly larger for warm episodes than cold episodes, although the magnitudes were small in both cases.

[29] Our findings are consistent with the results from several recent studies of ENSO impacts on wind resources in the Northern Plains of the United States [*Harper*, 2005; *Harper et al.*, 2007] and in the Southern Canadian Prairie region [*St. George and Wolfe*, 2009]. These studies have also found a general decrease of mean wind speed and wind energy production and an increase in the probability of low-wind events during the warm phase of ENSO. The lower near-surface winds in this region during El Niño events are consistent with slower upper level winds resulting from changes in large-scale circulation patterns. The pressure patterns during El Niño episodes are characterized by a deeper than normal Aleutian low, a stronger and eastward shifting Canadian high, and negative height anomalies over U.S. southwest. The upper atmospheric circulation pattern is typically characterized by a split of the jet stream over North America with a weaker branch diverted northward into Northern Canada, whereas the subtropical branch moves southward, leaving the Great Lakes region in between the two jets [*Shabbar et al.*, 1997].

4. Wind Power Potentials of the Great Lakes Region

[30] Estimates of potential wind resources are typically expressed in seven classes, with each class representing a range of mean speed as defined in Table 3. According to the current wind energy industry standards, class 1 (with annual mean wind speed at 80 m level less than 5.9 m s^{-1}) is considered unsuitable for wind power development, class 2 (with speed between 5.9 and 6.8 m s^{-1}) is regarded as marginal, and class 3 (with speed greater than 6.9 m s^{-1}) is considered suitable. *Archer and Jacobson* [2003, 2005] used the seven classes to quantify the global wind power. Using the annual mean wind speed at the 80 m height level, we calculated the percentages of the occurrences for each class over the 30 year period at each NARR grid point. The

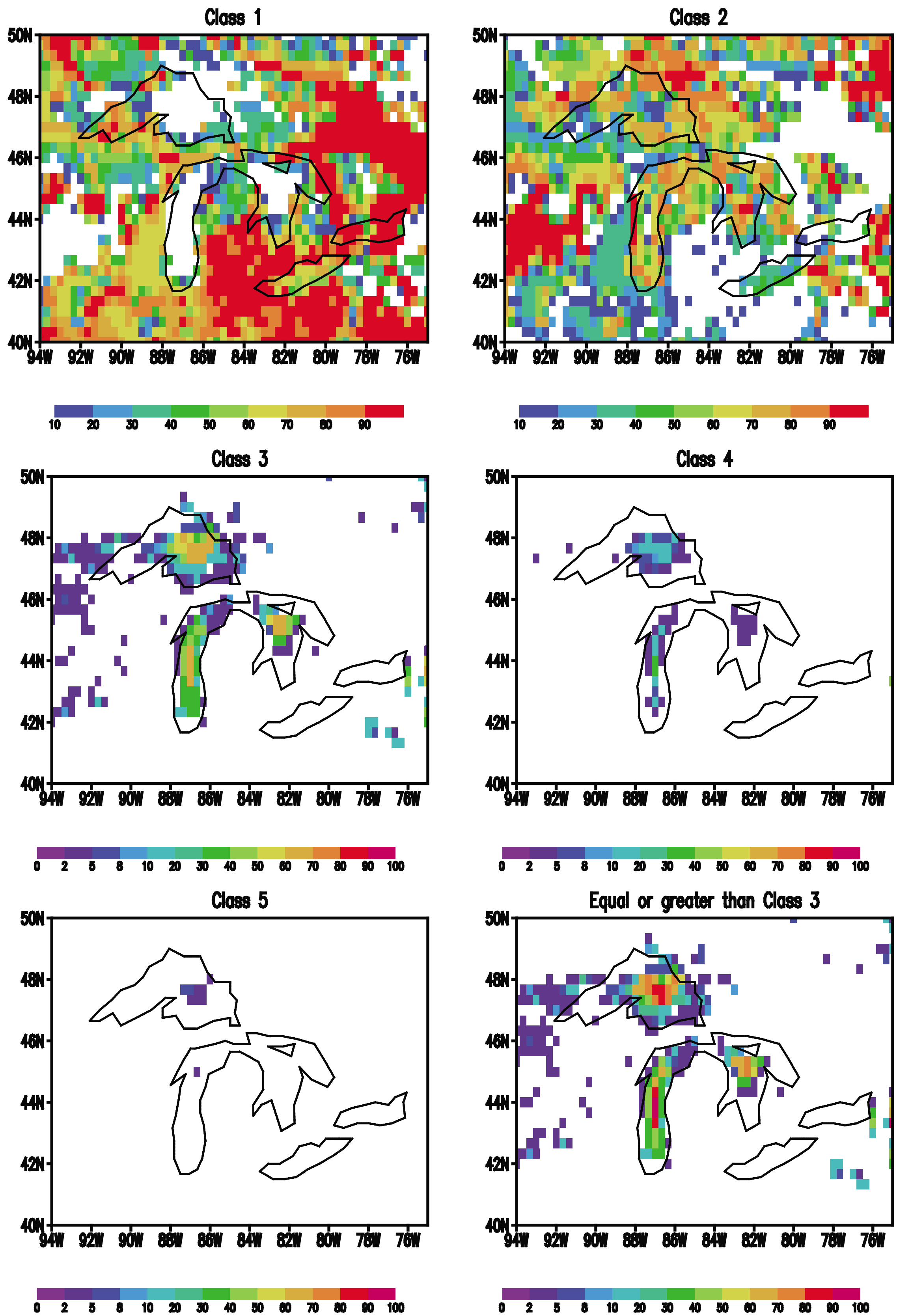

Figure 14. The percentages of wind speeds that fall into each wind power class.

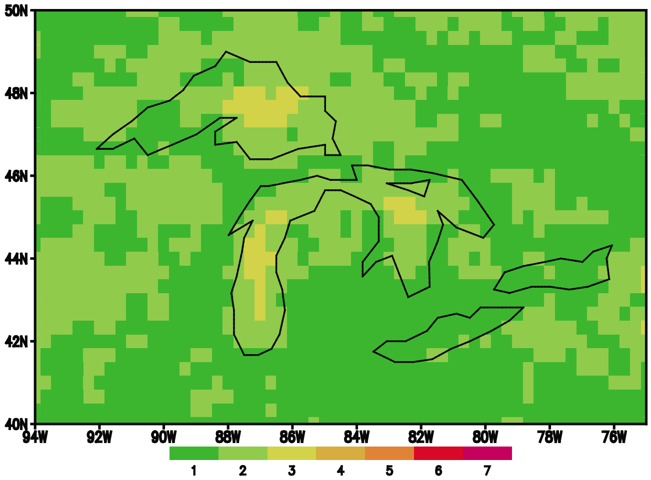

Figure 15. The climatology of wind power class for each grid point in the domain as determined from the 30 year averaged annual mean 80 m level wind speed from NARR.

spatial distributions of the percentages separated by class are shown in Figure 14. The majority of grid points over land fall under either class 1 or class 2 in all years. Areas west of Lake Superior in Minnesota and northern part of Iowa are classified as class 3, but the percentage of time in a year when this happens is low (5%). Grid points falling into classes 3 or above for more than 20% of the time are almost exclusively over the lake areas, especially Lake Superior, Lake Michigan, and Lake Huron. Figure 15 shows the wind class for each grid point based on 30 year averaged annual mean 80 m wind from NARR. Among the total of 1789 NARR grid points over the region, 1028 grid points (57%) fall in class 1, 731 grid points (41%) belong to class 2, and only 39 (2%) to class 3. All class 3 points are found over the center of Lake Superior, Michigan, and Huron. There are no NARR grid cells with a 30 year wind speed climatology in classes 4–7; in other words, all grid cells have 30 year wind climatology less than 7.5 m s^{-1}.

5. Summary and Conclusions

[31] This study took advantage of the relatively recent release of a high-spatial and temporal resolution, dynamically consistent, long-term meteorological and climatological data set to document the climate and climate variability of 80 m level wind fields over the Great Lakes region of the United States. Using 30 year continuous wind records from NARR, the study examined the seasonal and interannual variations and the spatial patterns of these variations. The study investigated impact of ENSO on variability of the 80 m level winds on an interannual time scale. Despite the fact that wind is an inherently noisy variable that is affected by both large- and local-scale conditions, the analyses revealed some common characteristics of 80 m level winds over the Great Lakes region.

[32] The results revealed a clear seasonal variation of 80 m level winds. Stronger mean winds appear in winter and early spring with the highest (6–7 m s^{-1}) occurring in November through January. Summertime winds are generally weak, with July and August being the 2 months when the lowest mean wind speeds (4–5 m s^{-1}) occur. The spatial variability of the annual mean winds is small across the entire region, and the spatial variability appears to be dominated by land-water differences with winds over lake surfaces consistently higher than those over land. The largest spatial variability across the region occurs in the fall season (September-October-November).

[33] In addition to year-to-year variations, the results also revealed three periods when the annual mean winds either oscillated around the normal value (1979–1991), were below the normal value (1992–2001), or were above the normal value (2002–2008). Larger interannual variability was found during the winter months (DJF), whereas smaller variations were seen in mid to late summer (July and August). The largest year-to-year wind speed variations occurred over the areas of the Great Lakes. There is a moderate correlation between the interannual variation of the wind speed and the temperature gradient between land and lake surfaces.

[34] The linear trend analyses for the windiest month (January) indicated an increasing trend everywhere in the region with the highest rate of increase over Lake Superior. The analyses for the calmest month (August) revealed a weak positive trend in the western and southern part of the region and a weak negative trend on the Canadian side of the Great Lakes region.

[35] The analyses suggested that there are some connections between ENSO and wind resources in the region. The major El Niño periods were characterized by lower mean wind speeds and more frequent occurrences of lulls and that El Niño events appear to have stronger influences on spring and winter season mean winds. The La Niña events appear to have a somewhat larger influence on summer season mean winds and a smaller effect on spring winds. The La Niña periods are also characterized by larger spatial variability in winds across the region. The interannual variability of 80 m winds also appears to be related to the variations of the average ice coverage over the Great Lakes, with above normal ice cover associated with slightly below normal wind speed and vice versa.

[36] Most of the region appears to be either unsuitable or marginal for wind energy development based on criteria established by wind energy industry, yet over Lakes Superior, Michigan, and Ontario, ample wind resources exist.

[37] Finally, it is worth mentioning that the study is limited by several factors. First, the NARR data, although a substantial improvement over the global reanalysis data sets, are still relatively coarse in resolution. Wind speed at local scales smaller than the 32 km horizontal grid spacing of the

Table 3. Wind Speeds Corresponding to Different Wind Power Classes at 80 m[a]

Class	Wind Speed at 80 m AGL (m s^{-1})	Suitability for Wind Power
1	$v < 5.9$	Unsuitable
2	$5.9 \le v < 6.9$	Marginal
3	$6.9 \le v < 7.5$	Suitable
4	$7.5 \le v < 8.1$	Suitable
5	$8.1 \le v < 8.6$	Suitable
6	$8.6 \le v < 9.4$	Suitable
7	$v \ge 9.4$	Suitable

[a]Following *Archer and Jacobson*, 2003.

NARR grid cells may be higher or lower than the wind speeds at NARR grid points that represent grid cell average. The 32 km grid spacing is also likely to smooth out spatial variations in wind fields and underestimate the influence from local topography, vegetation, and land-water contrasts. Second, although the 30 year record is sufficient for examining the mean climatology and interannual variability and subdecadal variation such as ENSO, it is not long enough to allow for an investigation into decadal or multidecadal variations possibly associated with large-scale oscillations such as North Atlantic Oscillation. The North Atlantic Oscillation has been found to play a role in modifying climate in central and eastern United States on the 15–30 year time scale and, as such, the oscillation is expected to lead to fluctuations in wind speeds over this time frame. Third, the slight negative bias of NARR 10 m winds as shown in the study by *Pryor et al.* [2009] and *Mesinger et al.* [2006] should be considered when interpolating the results here. Finally, as discussed earlier, the inability of NARR data set and other similar reanalysis data sets to reproduce the observed decreasing trend of near-surface (i.e., less than or equal to10 m) winds in most of United States, southern Canada, and Australia suggest that further studies are needed to understand the reasons for the discrepancies and whether similar discrepancy exists in 80 m wind trends.

[38] Despite these limitations, the results about the seasonal and interannual variations and the spatial distribution and the relationship to ENSO and ice coverage should prove useful to wind energy industry and energy policy makers.

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